Processing "fuzzy" material sets for environmental impact analysis of buildings

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ABSTRACT: Processing technical and environmental data on building materials, components, and systems has become more important during the last few years. Increased sensitivity towards environmental and energy problems has lead to the demand for simulation and evaluation of the long term behavior of buildings. The results of such simulations are expected to enable architects and engineers to develop a broader, interdisciplinary understanding of the impact of their products (buildings) on the environment. However, conducting such evaluations is currently hampered by the lack of comprehensive, up-to-date, and ecologically relevant data on building materials, components, and systems.

To address this problem, this paper proposes an approach to deal with the absent or uncertain attributes of building materials, components, and systems. In the past, various information systems have been developed to provide data on a limited set of building materials, including precise values pertaining to some of their characteristics, such as availability, manufacturers, costs, etc. These traditional information systems have difficulty in dealing with uncertain, incomplete and sparse data. However, uncertainty and incompleteness characterize the nature of most of the available and environmentally related characteristics of materials, components, and systems. In this paper, a fuzzy-logic-based augmentation of traditional information systems is proposed towards providing management, utilization and manipulation of incomplete and uncertain data.

INTRODUCTION

Compared to other modeling approaches, Zadeh's fuzzy set theory is more suitable for dealing with problems containing both qualitative and quantitative data, some of which may be precise while others may be uncertain. As with all models, the user has to evaluate the advantages and shortcomings of the fuzzy modeling approach. Before making use of fuzzy sets, one has to clarify the following:

(1) Why does one fuzzify a specific problem ?
(2) What specific part of the overall problem has to be fuzzified?
(3) Why does one prefer a specific type of fuzzy model ?

Once these general decisions are made, a method of converting a problem to fuzzy sets must be selected. There are two general methods for the development of fuzzy models. In the first method, which is based on the law of transition, fuzzy sets replace the precise attributes, but the relationships among variables are still expressed via ordinary mathematical equations. The second method, which is based on the law of cause and effect, relies on the law for operations with sets.

According to Terano et al. [1], a fuzzy model is ideally developed in two stages. First, sets and logical relationships are set up and second, the conversion to fuzzy sets is performed. Following this approach, the conversion to fuzzy sets, the interpretation of the model, and the interpretation of the results are easy.

MOTIVATION

The building industry uses a significant portion of resources for the construction and remodeling of buildings. Simulation and evaluation methods for efficient and meaningful resource use, if integrated in the planning and design process of architects and engineers, can contribute to the improvement of the environmental performance of buildings and their sustainability. The importance of the building industry should be illustrated with the following figures compiled in [2]. New construction in the United States of America represents approximately 8% of the Gross Domestic Product, or a total value of US$ 555 billion. A considerable portion of US is consumed by buildings. In the US, 35% of the total energy consumption in 1994 was used by buildings. It is obvious that the performance of a building and the long term durability of the building materials used can have substantial implications on global environmental problems and the sustainability of our communities.

Increased sensitivity towards environmental and energy problems has led to the demand for simulation and evaluation of the long term behavior of buildings. The results from such simulations are expected to enable architects and engineers to develop a broader, interdisciplinary understanding of the impact of their products (buildings) on the environment. However, conducting such studies is currently hampered by the lack of comprehensive, up-to-date and ecologically relevant data on building materials, components and systems. Furthermore, the evaluation of the long term behavior of buildings and their global environmental impact is not a procedure required by law or any other regulation within the building permit application procedure.

Although there exists a need for the evaluation of global environmental impacts of our built environment, most of the existing methods demand a large amount of detailed information. Although architects and engineers have access to a broad variety of data processing and communication technologies, the acquisition of data to support an environmental impact analysis of the life-cycle of buildings is a time and resource intensive procedure. All these problems have contributed to the fact that environmental impact evaluation is performed for only a few projects.

The following problems have to be solved in order to enable professional architects and engineers to conveniently and regularly perform environmental impact analysis:

(1) easy access must be provided to pertinent data sources by using common means of communication;

(2) methodologies must be developed that enable users to deal with uncertain data from various available data sources;

(3) manufacturers of building materials must be encouraged, or urged, to provide non-proprietary data for public use; and

(4) methodologies must be developed that fit in the existing planning and design framework of architects/engineers and which use common technical terms.

METHODOLOGY

The project described in this paper started with a knowledge acquisition phase in three areas:
(1) existing software for the evaluation of environmental impact;
(2) analysis of available data sources and a classification of their data structures; and
(3) existing evaluation methods for modeling the environmental impact of buildings.

As a model to guide our further work, and as standard of comparison with an existing software project, we used the Total Emission Model for Integrated Systems (TEMIS) [3] and GEMIS[4]. Both products are a result of a major research project on the environmental analysis of energy systems, started by the Öko-Institut in cooperation with the Environmental Systems Research Group at the University of Kassel in 1987. TEMIS evaluates environmental impacts (such as air pollution, greenhouse gases, solid waste and land use) of energy, transportation and materials systems. We decided to use these sources because they contain data and descriptions/definitions of manufacturing processes for building materials. However, because of the different orientations of these software tools, which have been developed for the evaluation of high voltage power-generation methods, they entail certain assumptions that could not be adapted in our work.

The basis for our analysis of available data sources was a publication of the Risk Reduction Engineering Laboratory of the U.S. Environmental Protection Agency (EPA) [5]. The document contains references to on-line databases, off-line databases within the USA and abroad, as well as further on-going studies. Profiles of approximately 40 on-line databases are described. Although Life-cycle Assessment (LCA) is generally defined in [5] as "..*a method for identifying, evaluating and minimizing the environmental consequences of resource usage and environmental releases with a product, process or package,"* we came to the conclusion that most of the data sources focus on industries other than manufacturers of building materials.

Within our work, we adopted a general classification of data in two groups, as per [5] - primary data and secondary data. Primary data are classified as plant or process-specific data. In this case, one assumes that the user of the data can directly access and/or influence the data collection process. Publicly available data, which have not been collected for a specific purpose (such as conducting LCA) are classified as secondary data. The assumption for this type of data is that the user of such data has no input into the data collection process.

For our future work, we assume that users will have access to several secondary data sources which describe products and processes within the A/E/C-industry.

A detailed description of available environmental impact evaluation methods is compiled in [2]. The scope of this paper is limited to data processing and does not include the evaluation of its results.

Fuzzification of building material sets

As mentioned before, one important goal of our work is to deliver a methodology that uses existing communication and data processing technologies and combines these separate technologies in a way that enables architects/engineers to include environmental impact analysis in their planning and design activities.

First, the analysis of existing software packages showed us that very detailed specifications of building materials and their manufacturing processes are necessary as input values. Conventional approaches are particularly problematic if composite materials with several basic components have to be considered. On the other hand, it is necessary to differentiate between the various existing manufacturing processes in order to achieve realistic results.

If we also take into consideration the fact that there exists no law or regulation that requires an evaluation of the long term environmental impacts of a building, it becomes obvious that architects and engineers will have to be encouraged to conduct such evaluations. Providing information systems that assist in these evaluations may provide some encouragement.

To support such an evaluation, these information systems will have to be:
(1) user friendly in order to be performed easily in the building delivery process;
(2) expandable in the sense that more detailed process descriptions can be gradually included in the evaluation; and
(3) expandable in the sense that more specific data (accessible through the several networks and provided by environmentally responsive manufacturers) can be obtained.

With these definitions in mind, we developed a usage scenario for such an information system, shown in Fig.**1**.

In order to relieve professional architects / engineers from compiling data about building materials, systems and components, we propose that data should be compiled, stored and managed by manufacturer-independent organizations. Besides the advantage that the professional architect / engineer will not have to compile the data, he/she will have access to a homogenous data source (database), he/she will only have to deal with one interface for the data exchange, and the cost for the use of external network services can be decreased.

As a first step, we developed fuzzy set-based input algorithms (fuzzification algorithms) that should enable manufacturer-independent providers of building material data sources to deliver environmental data sets to users (see Fig. 2). Because there exist no laws or regulations for manufacturers to provide data about the environmental impact of their products, which means that the data about products will likely be incomplete, we decided to use input algorithms based on fuzzy set theory. The left and right spread of fuzzy values illustrates the risk / uncertainty to the architect / engineer who uses this data. Furthermore, the fuzzy set approach is extendible: (1) when more detailed data / information is available, or (2) when more detailed information is necessary.

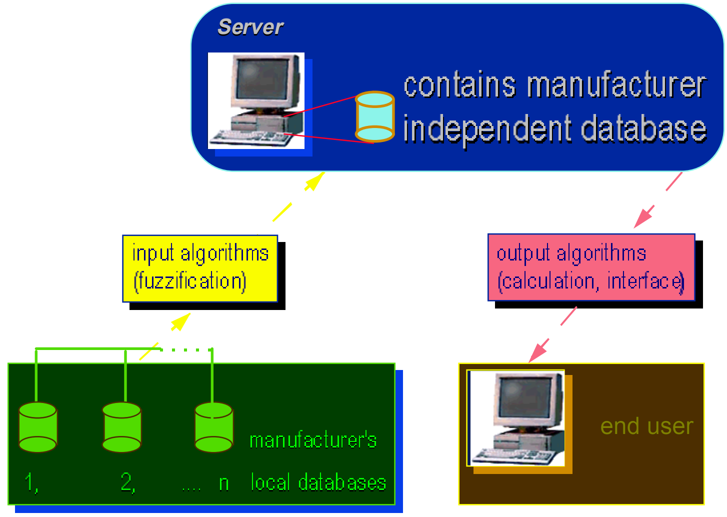

Fig. 1: Use Scenario of the Material Evaluation

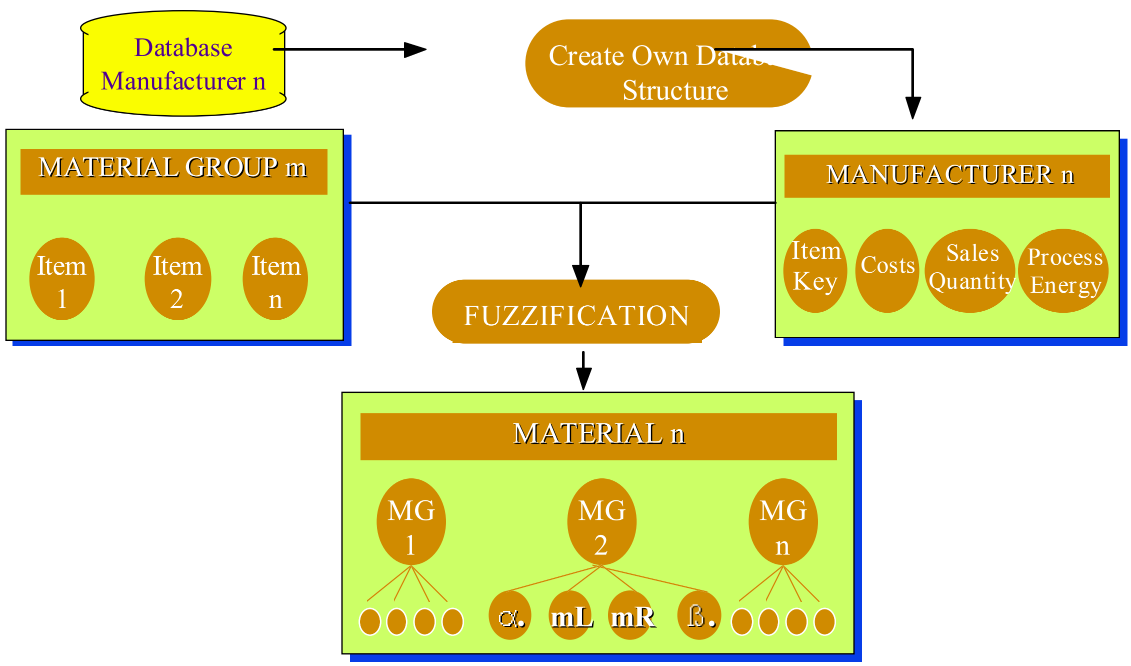

Fig. 2: Input Fuzzification Algorithms

The use of exact statistical operations in this case is not possible because large, complete, carefully evaluated data sources are currently not available. The main part of our work within our first project phase focused on the generation of fuzzy numbers for the emissions and embodied energy of composite building materials. Composite materials are able to be delivered to meet a variety of specifications making use of various quantities of constituent materials. Concrete, for example, is made up from cement, water, chemical additives and aggregates to form a variety of concrete mix designs with different properties. Each manufacturer of concrete is able to provide information on his sales volume for each component material with respect to her / his total sales volume. For the definition of membership functions of composite building materials, we used a very practical approach that is partially derived from an approach taken by Lave et al. for doing LCA using economic inputs and outputs for an entire economy [6]. This sales ratio is used as a "weight" for that component material in the membership function that represents the composite building material.

Initially, we assumed that these component membership functions can be approximated by a trapezoidal fuzzy membership function represented by 4 parameters: the upper and lower value of the uniformly distibuted range of values, the left spread and the right spread (α, β, mL, mR). By using relative sales amounts of component materials, we are able to deliver a general description of a composite material, such as concrete. These general composite material descriptions can then be used by an architect in early design phases to compare the environmental impact of several different composite building materials for use in a building.

If more manufacturer data are included, the data-source becomes more precise. In case the professional architect / engineer would like to perform an evaluation of the environmental impact of her / his design in later design phases, it is possible to use the same algorithms by using:

(1) a smaller amount of data that is applicable only for a carefully defined geographical region, or

(2) crisp data (fuzzy values without left and right spread and one mean value) for a completed design for which the material manufacturers are already determined.

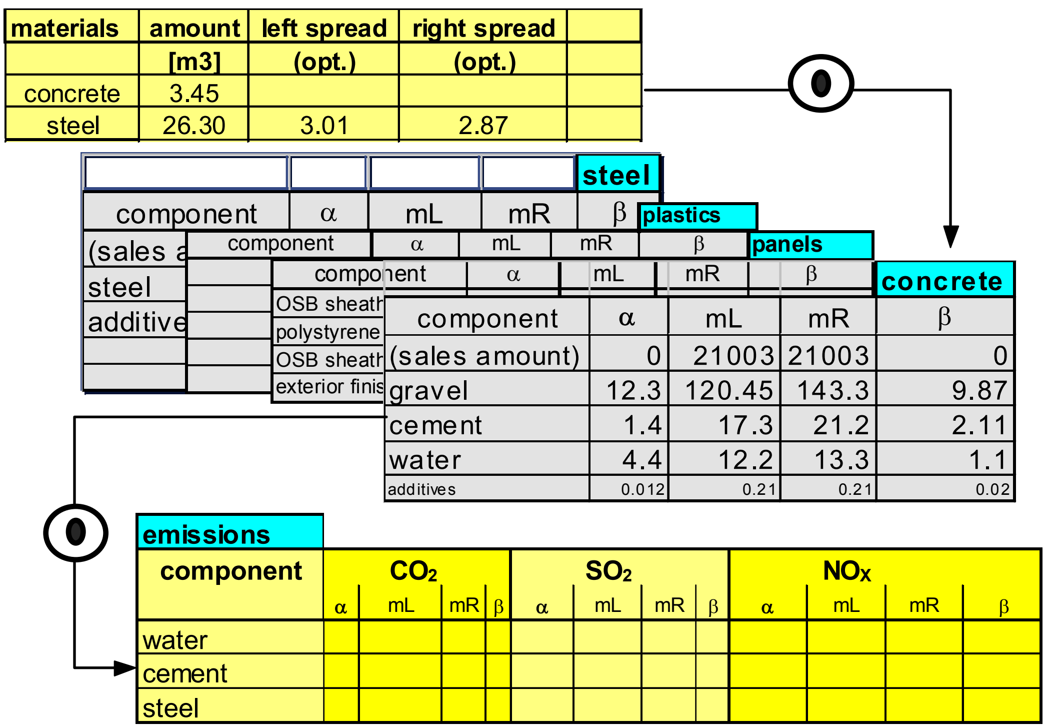

Fig. 3: Output: Calculation of Emission Values Using Fuzzy Material Descriptions and Fuzzy Operations

The regionally dependent data sets are pre-calculated. In case one or more manufacturers deliver new or updated information, the pre-calculation algorithms are activated based on these actions. The user, who accesses the stored results of these calculations, gets in each case the most up-to-date version of these building material sets. Another type of user support we feel is needed is "generated material choices," by which the professional architect / engineer can obtain an environmental impact by only specifying the floor space and the type or subtype of building, such as single family house, with brick foundation, panelized walls and two floors. Predefined shares for each important building material, system and component that is used can then be retrieved from within the database and used to compute the emissions and embodied energy of the design.

RESULTS

Given the exploratory nature of the present study, we first developed an approach for the fuzzification of certain parts of a total environmental impact evaluation model for buildings. Given the results of our problem analysis, our work became focused on the development of a data input model that enables a user to work with uncertain information regarding various composite materials. We focused our work in this way because the availability of on-line, independent data sources is one of the most important prerequisites in order to enable professional architects / engineers to easily and quickly perform environmental impact evaluations.

As the second step in this work, we began to develop output algorithms for the calculation of environmental impact data for a specific building using the manufacturer-independent database. The complete calculation is depicted in Fig. 3. As mentioned earlier, rough and quick calculations in early design stages can be easily performed by using pre-specified values for the share of the amount of certain building materials used within specific types of buildings.

FUTURE WORK

In our first project phase, we implemented a simplified version of the emission calculation as shown in Fig. 3. In this prototypical test implementation, we use only fuzzy values for the definition of the composite materials (described in the tables in the center of Fig. 3). Currently we use crisp values for the definition of the share of the specific building materials (shown in the upper table of Fig. 3) and the definition of emission values (shown in the lower table of Fig. 3). Thus we do not have to perform a fuzzy multiplication. In future phases of this project, we will investigate which of the available methods for fuzzy multiplication will be the most appropriate for the calculation of emission values and the embodied energy of buildings. We will also investigate the available data sources on the INTERNET in order to acquire a sufficient amount of information on building materials, systems and components.

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